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Defense Technical Information Center
Building 5, Cameron Station
Alexandria, VA 22314

To Whom it May Concern:

Enclosed please find the Final Technical Report for ONR Grant N00014-91-J-1006. Additional copies have been forwarded to the Scientific Officer, the ONR Regional Office, and the Naval Research Laboratory.

Sincerely,

Carl Wieman

Carl E. Wieman
Professor of Physics and
Fellow of JILA

cc: Jan Farrar, CU Contracts and Grants

Final Technical Report:

1. Title of Grant: Spontaneous Force Optical Traps
2. Principal Investigators : Carl E. Wieman and Eric Cornell
3. R&T Code: 3122024 Grant # N00014-91-J-1006
4. Funding profile:
   Total amount of Grant: $375,143
   Year 1- $121,938
   Year 2- $124,547
   Year 3- $128,658

Capital equipment item	Purch. Date	Cost
MODULATOR AD NEOS N23110-HS	1193	808
HRD CAMERA SYSTEM ELECTRIM	0394	860
RETARDER VARIABLE THORLABS CR100	0495	914
MODULATOR A-O NEOS N15260	0995	800
ISOLATOR OPTICAL ISOWAVE I-80T-4	1195	1,710
ISOLATOR OPTICAL ISOWAVE I-80U-4	1195	2,462
COMPUTER SYSTEM GATEWAY P5-133	0396	2,425

5. Technical objective:
- Develop new techniques for cooling and trapping atoms.
- Produce and study Bose-Einstein condensation in low temperature gases.

6. Published papers resulting from this support (numbers only):
   a. Submitted but not published___4___
   b. Published in refereed journals___15___
   c. Published in non-refereed journals___0___
7. Number of technical reports submitted___0___
8. Number of books written___1___
9. Number of book chapters written___2___
10. Patents as a result of this work
    a. Number of applications filed___2___
    b. Number of patents granted (include patent number and date of patent):___1___ S. Chu, W. Swann and C. Wieman, "Frequency standard using an atomic fountain of optically trapped atoms", Patent #5,338,930, August 16, 1994

11. Total number of presentations given___44___ List 1 - 3 of the most significant. Include forum, date, title, and a couple of sentences describing the significance of the presentation.

    a. E. Cornell, "Evidence for Bose-Einstein Condensation in ultra-cold rubidium gas", 12th Int. Conf. on Laser Spect., Capri Italy, June 1995. This was the first announcement to the scientific community of Bose-Einstein condensation in a gas. It created great excitement and was by far the most notable result at the conference.

    b. C. Wieman, "Bose-Einstein condensation in an ultracold gas", AAPT annual meeting, Reno Nevada, Jan. 1996. This was the Richtmyer Lecture Award, given annually by

the Association of Physics Teachers in recognition of a major scientific accomplishment and exceptional lecturing ability.

c. C. Wieman, "Bose-Einstein condensation in an Ultracold Gas", APS annual meeting (plenary lecture), Indianapolis, May '96. This was a special plenary Unity of Physics Lecture, one of only two plenary scientific lectures offered at the meeting.

12. Honors and awards received during the granting period:
(Underlined items resulted at least in part from ONR funding.)

<u>Cornell</u>
<u>1) Elected Fellow of JILA. (Univ. of Col.) 1994</u>
<u>2) Stratton Award (NIST) 1995</u>
<u>3) Zeiss prize (Zeiss Corp). 1996</u>
<u>4) Promoted to Professor of Physics adjoint.(Univ. of Col.) 1996</u>
<u>5) London Prize for Low Temperature Physics (IUPAP) 1996</u>

<u>Wieman</u>
1) Elected Chair, Joint Institute for Laboratory Astrophysics, 1993-1995
<u>2) E. O. Lawrence Award in Physics (DOE) 1993</u>
<u>3) Davisson-Germer Prize (APS) 1994</u>
<u>4) Elected to National Academy of Sciences 1995</u>
<u>5) Einstein Medal for Laser Science (Soc. for Opt. and Quant. Elec.) 1995</u>
<u>6) Richtmyer Memorial Lecture Award (Am. Assoc. of Physics Teachers) 1996</u>
<u>7) London Prize for Low Temperature Physics (IUPAP) 1996</u>
<u>8) University of Colorado Distinguished Research Lectureship (Univ. of Col.) 1996-7</u>
<u>9) Elected vice-chair elect (to move up to Chair in 2 years) of DAMOP of APS. 1996</u>

It might also be noted that in its annual ranking of graduate programs, US News and World Report ranked the University of Colorado AMO Physics Program as #1 in the country. This was largely as a result of the work of Cornell and Wieman.

13. Number of different post-docs supported at least 25% of the time for at least one calendar year___2___. Estimate total person-months of post-doc support under this grant___36___.

14. Number of different graduate students supported at least 25% of the time for at least one calendar year___2___. Estimate total person-months of graduate student support under this grant___36____.

15. List 2 - 5 of the most significant publications resulting from this work: Include titles and full citations, as well as a few sentences indicating the significance of the publication.

1. M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman and E. A. Cornell, "Observation of Bose-Einstein condensation in a dilute atomic vapor", Science, <u>269</u> 198-201 (1995). This paper reported the first creation of a Bose-Einstein condensate in a gas. It

was featured on the front page of most major newspapers throughout the world.

2. D. Jin, J. Ensher, M. Matthews, C. Wieman, and E. Cornell, "Collective excitations of a Bose-Einstein condensate of a dilute gas", Phy. Rev. Lett., July 28, 1996. This paper reports the first observation of elementary excitations of a Bose condensate and is a major step towards developing a full understanding of the dynamical behavior of condensates.

3. W. Petrich, M. Anderson, J. Ensher, and E. Cornell, "A stable tightly confining magnetic trap for evaporative cooling of neutral atoms", Phy. Rev. Letters 74, 3352 (1995). A new type of magnetic trap, called a time orbiting potential (TOP) trap was developed by the authors. This trap allowed evaporative cooling of a trapped atom sample to lower temperatures than had ever before been achieved, and opened the way to the creation of Bose-Einstein condensation.

16. Major accomplishments:

•Gravitational Sisyphus cooling was successfully demonstrated. This is a new cooling scheme, which is notable in that it is the first optical cooling scheme for magnetically trapped atoms.

•The first measurement of the S wave elastic scattering cross section for rubidium atoms was completed.

•A technique for greatly reducing the collisional loss rate from a vapor cell MOT was demonstrated. This allows more atoms to be captured under UHV conditions and extremely long trap lifetimes to be obtained.

•A compressed MOT was demonstrated. In this device, by proper tuning of the lasers and increasing the magnetic field gradients, the density of atoms in the MOT was increased by more than a factor of 10.

•A new type of magnetic trap, called a time orbiting potential (TOP) trap was developed. This trap provides stable strong confinement allowing evaporative cooling of a trapped atom sample.

•The most important accomplishment was the observation of Bose-Einstein condensation in a dilute vapor. This was achieved by evaporatively cooling a sample of magnetically trapped rubidium atoms to below 200 nK. These results were widely recognized in the scientific and popular press. The work was published in Science 269, 198 (1995), the cover of which was a color image showing our results. We have nice color view graphs available showing the apparatus and the results from this work. It was recognized by Science as the most important scientific discovery of 1995, and Science News rated it as the most important accomplishment in physics for 1995.

•We have studied three properties of the Bose-Einstein condensate in a rubidium gas. These are the first quantitative measurements which have been made on condensates. First was the observation and study of the phonon-like collective excitations of the condensate, second was the

measurement of the distortion of the condensate wavefunction due to interactions, and third was the determination of the fraction of atoms in the condensate ground state as a function of temperature.

•A new apparatus using a multiply loaded double MOT has provided much larger condensates, while still using inexpensive low power diode lasers. This technique is likely to become the standard tool for producing and studying BEC in the future.

17. Transitions: We received a patent for a slow atom cesium atom clock based on our diode laser technology and vapor cell MOT developed under this grant. This patent was licensed by Rincon Research Inc. which is developing this into a commercial product.

18. Summary of the overall impact of your work in this period.
We have created a major new area of research, the study of Bose-Einstein condensation in ultracold gases. Many groups are investigating this novel state of matter and all the experimentalists are using the techniques we pioneered for producing and studying the condensate.

19. Four (4) key words/phrases describing your project.
Laser cooling
Atom trapping
Bose-Einstein condensation
Ultracold temperatures

20. Provide three (3) viewgraphs highlighting the science and technology associated with the overall project.
Please see following pages.

Final Report on Spontaneous Force Optical Traps

PIs : Carl Wieman and Eric Cornell

R&T Code: 3122024, grant # N00014-91-J-1006

Objectives:

- Develop new techniques for cooling and trapping atoms.
- Produce and study Bose-Einstein condensation in low temperature gases.

Approach:

- Experiments using laser light forces to manipulate atoms.
- Combine with trapping by magnetic fields, cooling by evaporation.
- Analyze optical images of resulting clouds.

Accomplishments:

- Demonstrated first optical cooling scheme for magnetically trapped atoms.
- Invented better magnetic trap (TOP trap). Cooled atoms to a few nK.
- First observation of Bose-Einstein condensation in a gas
- First studies of BEC properties.
- Invented low cost technique for producing large amounts of BEC based on double MOT.

Impact and transitions:

- Creation of BEC in a gas recognized as the most important scientific discovery of 1995 (Science magazine-AAAS).
- BEC in gases- new rapidly growing research field.
- Patent for a slow atom cesium atom clock granted and licensed.

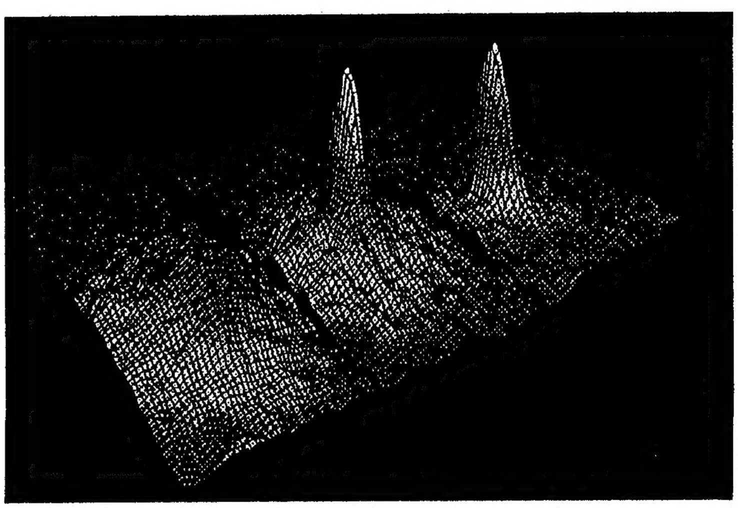
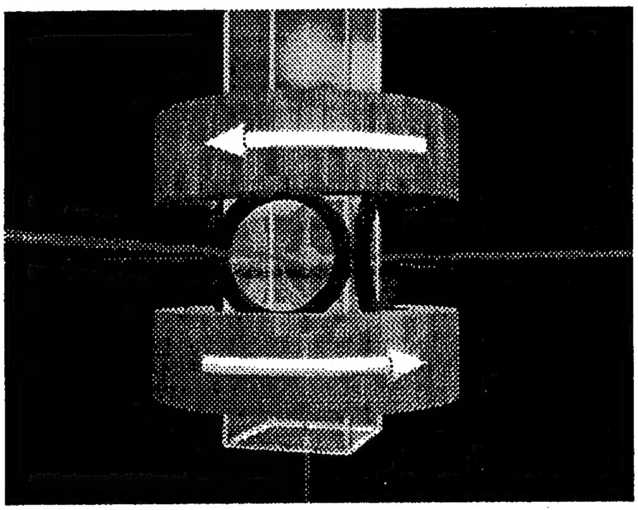


Image of BEC

Creation of Bose-Einstein condensate

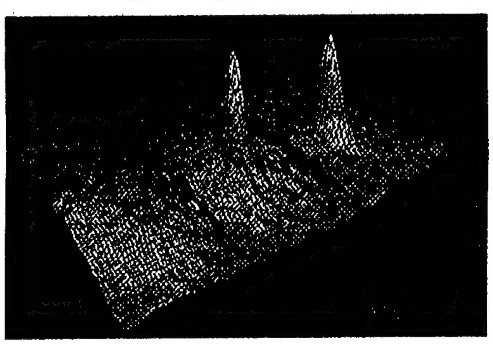
- All atoms in single quantum state.
- Quantum behavior on macroscopic scale.
- Simple inexpensive technology
    - diode lasers and vapor cell optical trap.



Bec Apparatus

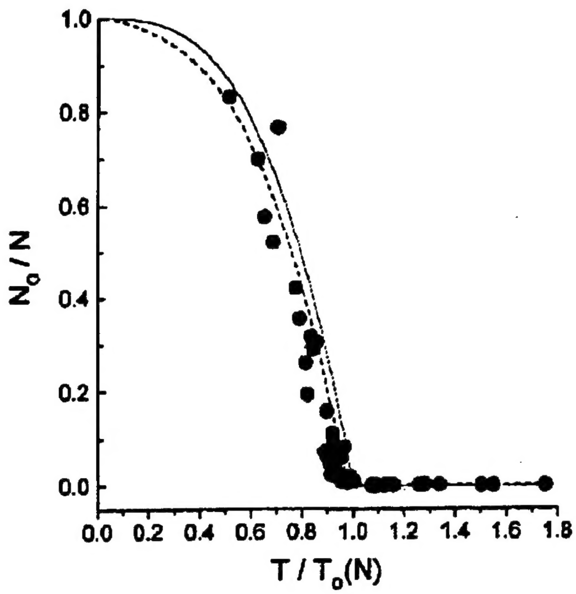
Steps to BEC:

1. Laser cool and trap sample in middle of cell.
2. Optically compress.
3. Load into magnetic trap- currents through blue and green coils, laser light off.
4. Evaporatively cool.
5. Expand and image trapped cloud.



Measurements of condensate properties

• Fraction of atoms in lowest quantum state versus temperature



•Study of oscillation modes of condensate.

1. Rapidly squeeze condensate.
2. Stop squeezing and watch condensate oscillate.

Determined frequencies and shapes of modes.

Measured density dependence.

Measured decay time of oscillations long
 -first step toward superfluid.

• See resonanat frequencies shift with density

Explanation of viewgraphs.

VG1 Image at the bottom shows pictures of three clouds of rubidium atoms. The leftmost picture shows a cloud cooled to 200 nK above absolute zero. The middle picture is 100 nK. The narrow peak in the center is the Bose-Einstein condensate. The leftmost picture is a cloud cooled within a few nK of absolute zero. All the atoms have Bose condensed.

VG2 List of notable features of a Bose-Einstein condensate.

Picture of the heart of the BEC apparatus.

The experimental procedure used to produce and observe the images of BEC shown.

VG 3 Two examples of measurements that have been made on condensates.

Top shows the fraction of the atoms which are in the ground quantum state vs temperature of the sample, along with theoretical predictions.

Bottom describes how the elementary oscillation modes of the condenstes have been observed, and what aspects about them have been measured.